NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-255

An Experimental Correlation of the Nonreactive Properties of Injection Schemes and Combustion Effects in a Liquid-Propellant Rocket Engine

Part VI. The Relation Between the Starting Transient and Injection Hydraulics

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ABSTRACT

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Starting-flow-transient criteria for gas-pressurized liquid-bipropellant rocket engines are presented. These criteria are based on a consideration of the hydraulic characteristics of the propellant-feed system, with particular emphasis on the propellant valve, the injector, and the injector-manifold volume. The desirability of a short starting transient without chamber-pressure overshoot is presumed.

A nonreactive testing technique is presented for the evaluation of the starting-flow transient prior to the commitment of an engine to its initial firing.

Results of the application of both the flow criteria and the nonreactive testing technique in an injection research program utilizing a 20,000-lb-thrust rocket motor are also presented.

Author

I. INTRODUCTION

The operation of liquid-bipropellant rocket engines, regardless of size or feed-system design, requires a successful progression through what is termed the starting transient. A general discussion of this transient must concern itself with all the operations occurring between an initiation signal (i.e., fire switch) and the instant that conditions in the combustion chamber have achieved steady state. However, the primary concern is necessarily centered about the two elements that represent (1) the initiation of flow in the propellant supply system and (2) the ignition and consequent pressure generation within the combustion chamber.

Although the success of the start must be judged according to the requirements of the intended use for a given engine, it can be assumed that as a design objective, the chamber-pressure transient (and therefore thrust transient) should be short, predictable, and without overshoot.

If it is further assumed that the combustion-chamber transient is in phase with and proportional to the injected flow rates but supplemented by the relatively fast reaction of a quantity of propellant that may have accumulated in the chamber at the time ignition occurs, then it is possible to postulate several criteria that must be satisfied if the assumed transient is to be achieved. These postulates may be summarized as follows:

1. The propellant flow rate into the chamber must never exceed the intended steady-state value.

2. The quantity of propellant allowed to accumulate in the chamber prior to ignition must be negligibly small.

3. The mixture ratio – i.e., ratio of injected flow rates – achieved during, and subsequent to, ignition must be controlled.

If these limitations can be realized, it automatically follows that chamber pressure cannot exceed the intended steady-state value. It is further implied that accumulation of *either* propellant is disallowed in order to eliminate single-component decomposition as well as excessive combustion rates at off-design mixture rations. Thus, simultaneous injection and ignition at first injection are requirements. However, with regard to mixture ratio, it is not obvious that this variable should be maintained *constant*, but it is intuitively appealing, and probably sufficiently precise for design purposes, to assume that it should be constant. Obviously, if this condition is satisfied, it follows that the mixture ratio during the transient must have a value equal to the intended steady-state value.

Because all of these criteria are flow-dependent, *control* of the combustion transient is dependent upon the designer's ability to interrelate the hydraulic characteristics of the feed system, the propellant valve, and the injector with the physical and ignition characteristics of the propellants. Thus, although it is relatively easy to describe the gross features of an acceptable starting transient, the specification of the required flow characteristics is more difficult.

The need for a more quantitative description of such specifications was illustrated in the course of a performance evaluation of a series of injectors utilized in the so-called RMIR[1] program. Short transients were required for these experiments in order to maximize the duration of the steady-state portion of the 2- to 3-sec total run time that was feasible with uncooled hardware. Also, since one of the objectives of the program was to determine heat-transfer distributions by the transient-temperature-measurement technique (Ref. 8), it was essential that steady-state conditions at the wall, and hence in the chamber, be achieved as rapidly as possible. In the process of satisfying this experimental objective, most of the historically useful criteria for achieving "good starts" were tried but were found to be completely inadequate. It was determined, for example, that the "oxidizer lead" criterion was as unsuitable as the so-called "snap-opening valve" concept; and it was ultimately verified that "fuel lead" was an equally poor criterion for establishing the transient characteristics. With essentially every injector configuration, these starting difficulties were characterized by chamber-pressure overshoot, which often was severe enough to damage the feed-system plumbing or rupture chamber-joint seals; and of course it made little difference where the failure occurred since the damage to the test stand and experimental hardware was costly and time-consuming to repair.

It was therefore obvious that a much more knowledgeable control of the hydraulic transient and the chamber environment at the time of ignition was an essential prerequisite to the idealized rapid, monotonic, constant-mixture ratio, reproducible starting transient.

In an effort to define those parameters that must be controlled if such transients are to be achieved, a limited number of experiments were conducted as a supplementary part of the RMIR program. The results of these selected experiments are presented here together with several general recommendations and conclusions that appear to be verified by their application to several system configurations.

[1]The Rocket Motor Injection Research program (RMIR) represented an effort to demonstrate the applicability of data obtained with nonreactive sprays to the design of liquid-propellant rocket injectors. The various aspects of this effort have been reported separately in Ref. 1 through 7, which discuss respectively the properties of injection schemes as inferred from nonreactive-spray data, the experimental techniques and instrumentation, the gross performance characteristics, the relation of the injection scheme to chamber heat transfer, resonant combustion characteristics, the performance achieved by high-flow-rate elements, and the performance attained with the pentaborane-hydrazine propellant combination.

All tests were made using uncooled engine assemblies of nominally 20,000-lb thrust at 300-psia chamber pressure at the prevailing test-site ambient temperature and pressure. The propellants were supplied to the injector from an N_2 gas-pressurized system. The program was conducted at JPL Test Stand "B," Edwards Test Station, Edwards Air Force Base, California.

II. PREDICTING THE FLOW TRANSIENT

A. System Configuration

The feed system used for the RMIR program, which is also typical of a system required for any gas-pressurized bipropellant injection scheme, is represented schematically in Fig. 1. It includes gas-pressure regulators, propellant tanks, feed-line plumbing, propellant valves, injector manifolds, injector orifices, and the combustion chamber. A typical injector/chamber assembly as installed in the test stand for performance evaluation is shown in Fig. 2, while Fig. 3 shows the feed-line installation from the tank outlets to the propellant-valve inlet ports. Reference 2 provides additional descriptive details of the test stand and its associated systems.

Although the RMIR program utilized a number of different injector-propellant configurations that were required to operate over a wide range of initial conditions, a typical system incorporating a single injector is suitable for illustrating the relatively simple analysis that can be utilized to predict a hydraulic transient that will prevent overshoot and produce essentially simultaneous injection.

The appropriate system constraints as characterized by the static situation just prior to a firing (just before the propellant valve is opened) can be summarized as follows:

1. Propellant tanks are pressurized to provide the desired steady-state flow rates.

2. Feed lines from the tank to the entrance of the propellant valve are propellant-filled and pressurized to tank pressure.

3. Plumbing and injector manifolds and orifices downstream of the propellant valve are gas-filled at atmospheric pressure.

4. Chamber pressure is atmospheric pressure.

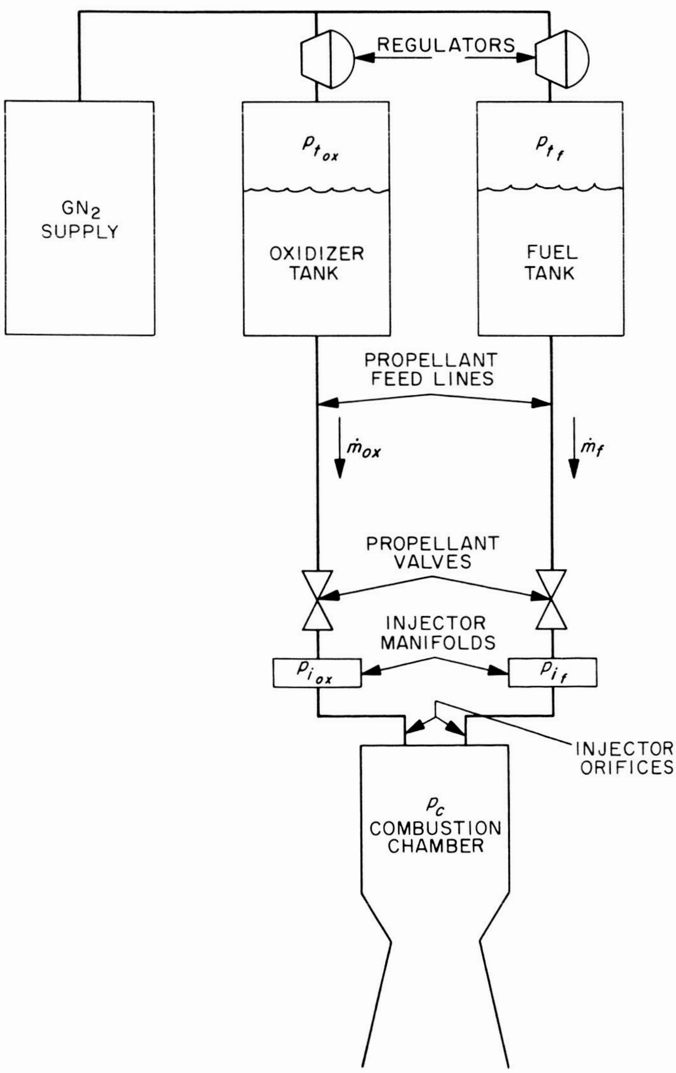

Fig. 1. Feed system schematic

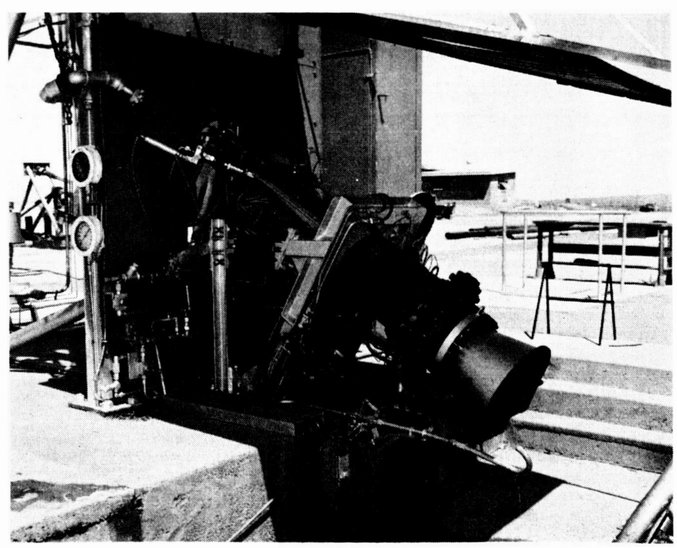

Fig. 2. RMIR Injector 5 test-stand installation

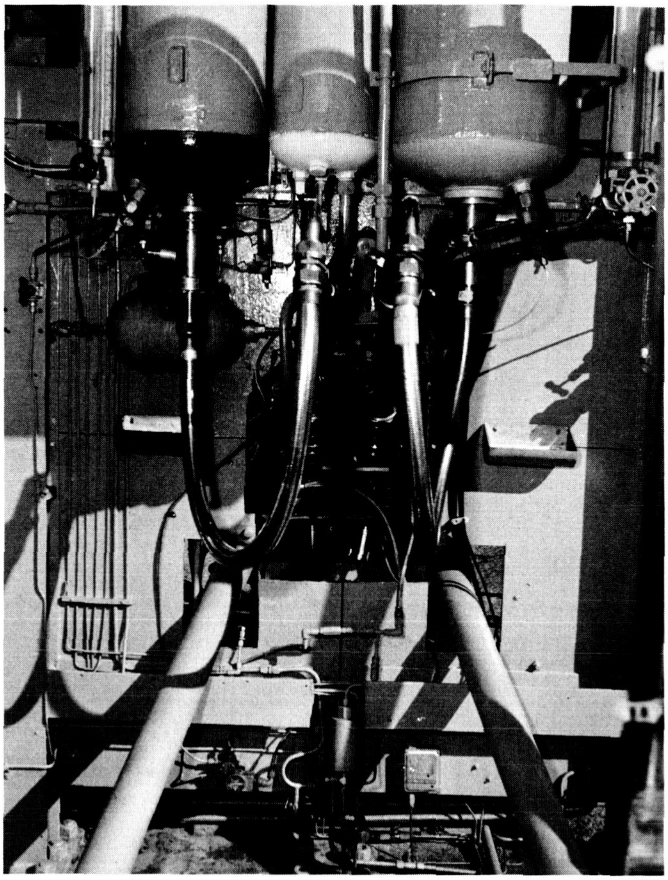

Fig. 3. Typical feed-line installation

The injector used for illustration in this Report is identified as RMIR Injector 5, for which the hydraulic-design specifications pertinent to this Report are listed in Table 1. The high pressure-drop characteristics noted in the Table result from the high friction losses sustained by the long L/d orifices. Photographs of the injector assembly and its face are shown respectively in Fig. 4 and 5. Additional design details of this injector are presented in Ref. 1, while its combustion performance is described in Ref. 3.

Although two different propellant valves were used during the RMIR program (both are described in Ref. 2), only the *dual ball valve*, which was used for the majority of the experiments, will be described herein. The other valve, used in early tests, was unsatisfactory for test-stand use from the standpoint of durability and control flexibility.

The complete ball-valve assembly, shown in Fig. 6, consists of two individual 2¼-in. (port diameter) ball valves manufactured originally by Hydromatics, Inc.[2] The individual valve assemblies are rigidly mounted together and operated by a common pneumatic actuating cylinder through an interconnecting linkage.

[2]Bloomfield, New Jersey.

Table 1. RMIR Injector 5 hydraulic design specifications

Parameter	Specification
Propellants	SFNA + Corporal fuel
Specify gravity at 70°F	
Oxidizer	1.553
Fuel	1.072
Dynamic viscosity at 70°F	
Oxidizer	0.95 ft²/sec
Fuel	4.90 ft²/sec
Mixture ratio	2.80
Total mass rate of flow	96.0 lbm/sec
Volumetric flow rates	
Oxidizer	0.73 ft³/sec
Fuel	0.38 ft³/sec
Type of injection elements	Unlike impinging doublets
No. of elements	52 (identical)
Impingement angle	44 deg
Resultant momentum angle	Parallel with chamber axis
Impingement-point plane	0.75 in. from face
Jet diameters	
Oxidizer	0.173 in.
Fuel	0.0986 in.
Free jet length	4 jet diameters
Orifice L/d	100
Overall injector pressure drop at design flow rates	
Oxidizer	252 psi
Fuel	410 psi
Manifold volumes	
Oxidizer	0.093 ft³
Fuel	0.059 ft³
Face diameter	11 in. (flat face)

To obtain the required control features, the original linkage was redesigned at the Jet Propulsion Laboratory to provide a lead adjustment which is continuously variable over a range of 33 deg (ball rotation) for either ball relative to the other. This redesigned linkage and the common actuating cylinder are shown in Fig. 7a. The photograph shows the adjustable cam-plate through which the variable lead is obtained. Figure 7b is a similar view with the cam-plate removed and illustrates how the lead is varied for one ball relative to the other by varying the cam-plate position in a direction parallel to the cylinder axis. Since the cylinder is symmetrically located between the two identical individual valves, exchanging the linkage components and inverting the cam-plate allows identical lead adjustments to be made for either ball.

The transport characteristics of this cam-controlled drive linkage are illustrated in Fig. 8. Note that the individual valve-opening rates are not adjustable independent of lead, since both valves complete full opening simultaneously regardless of lead setting.

An electropneumatic control system provides a nearly continuously variable, overall opening time (from start of leading valve to both valves fully open) through a practical range of 30 msec to 4 sec. This system is shown schematically in Fig. 9. The actuating piston is maintained in its valve-closed position by a spring force plus a differential pneumatic force. This latter force is established by the 100-psig-regulated N_2 supply pressure exerted on the

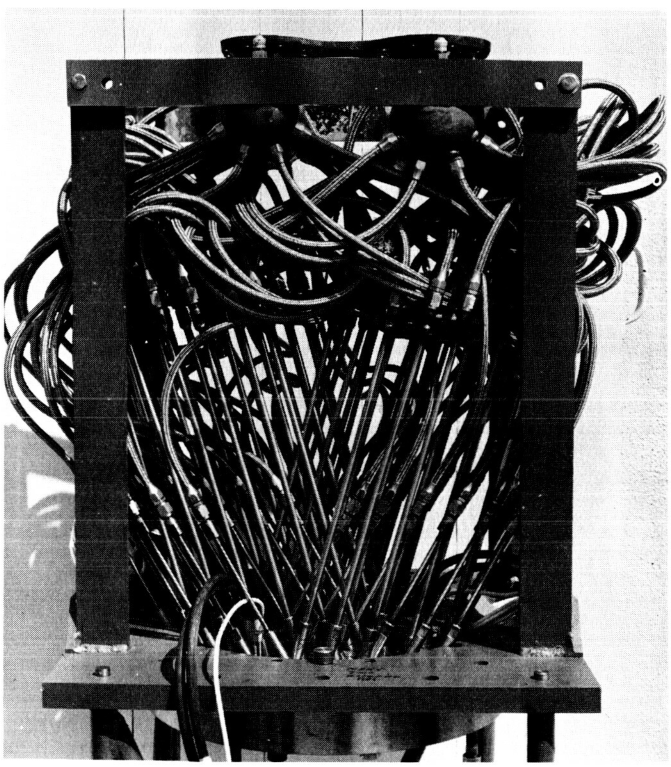

Fig. 4. RMIR Injector 5 assembly

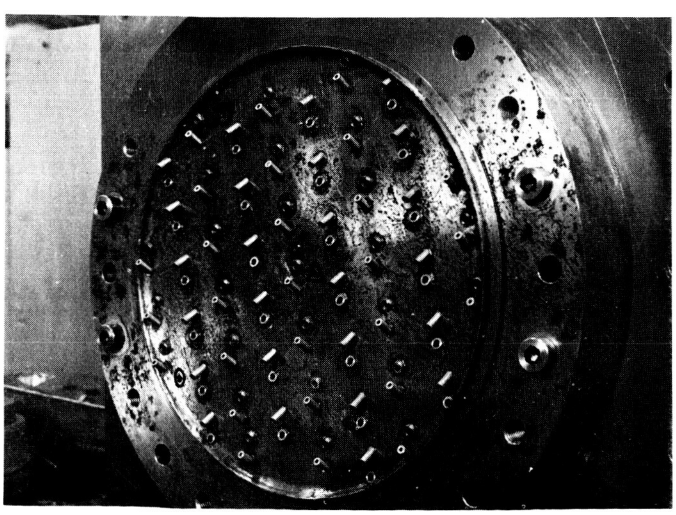

Fig. 5. RMIR Injector 5 face

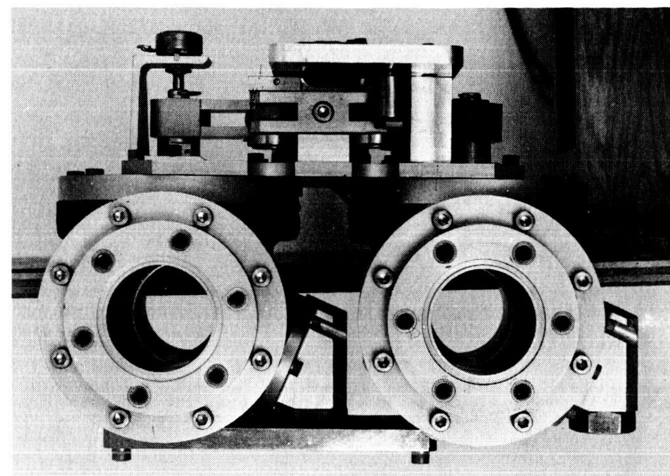

Fig. 6. Dual-ball-valve assembly (balls partially open)

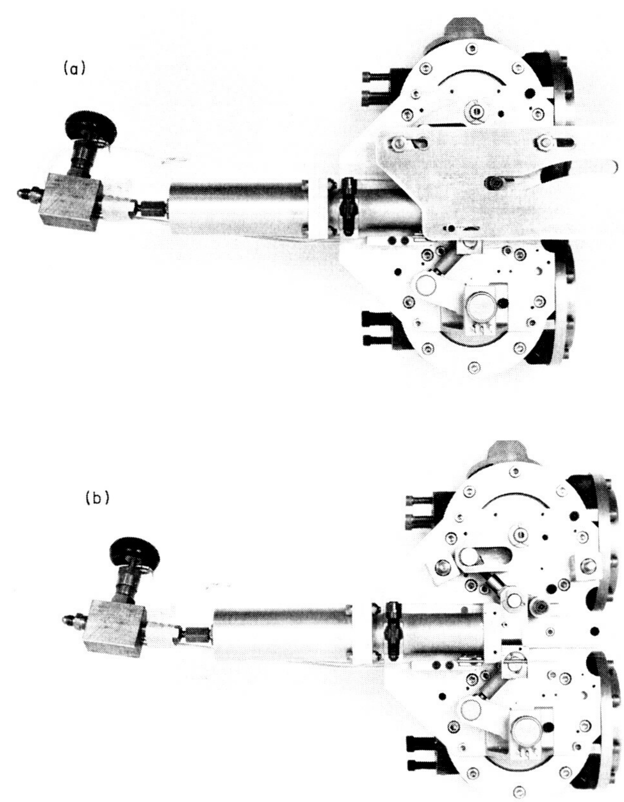

Fig. 7. Dual-ball-valve actuating linkage

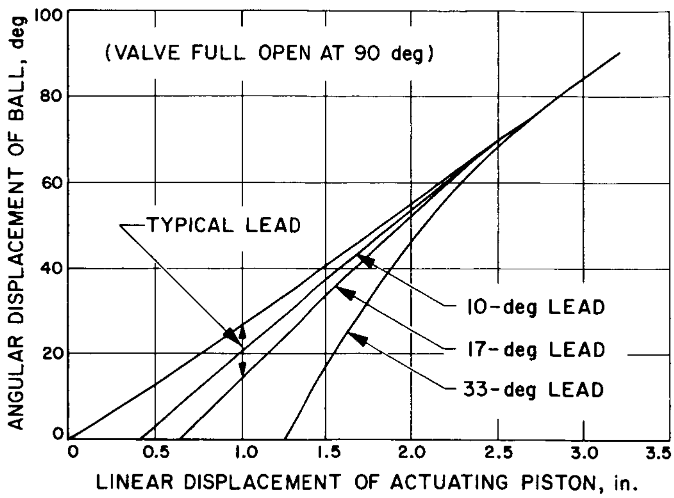

Fig. 8. Transport characteristics of cam-controlled drive linkage for dual ball valve

spring side of the piston minus a pressure on the opening side appropriately reduced by the bleed orifice. The accumulator is also pressurized to 100 psig.

When the control switch is actuated to open the propellant valve, the opening solenoid is energized, allowing 600 psig N_2 to flow through the control orifice and into the opening side of the cylinder — the control-orifice size having been selected according to the opening rate desired. As the actuating piston moves, the microswitch closes, arming the closing solenoid. The 100-psig pressure on the spring side of the piston is maintained relatively constant during the piston movement by the combined effects of the large accumulator volume and back-pressure relief of the preset regulator.

Both the prepressurization of the opening side of the cylinder through the orifice bleed circuit and the maintenance of a relatively constant back pressure on the piston during its opening travel were incorporated to promote linearity of the piston motion with time. Of course, the flow through the valves varies nonlinearly with the respective ball position owing to the circular shape of the ball port and the consequent variation of effective flow area as the port rotates past its seal. This nonlinearity is

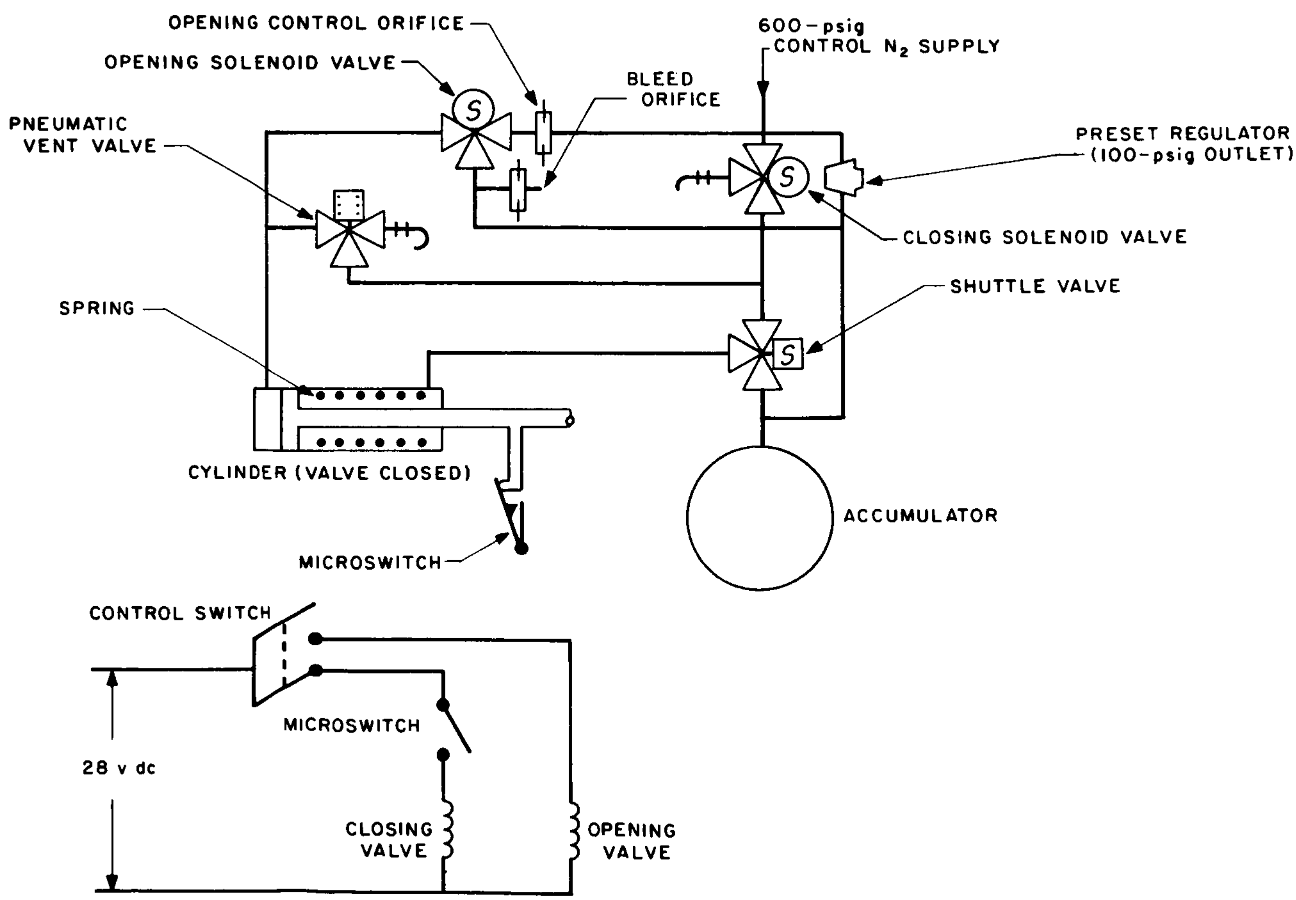

Fig. 9. Electropneumatic dual-ball-valve control system

illustrated in Fig. 10 for approximately the first half of a typical ball rotation toward the fully open position.

The valve-closure time is limited to a minimum value by the hydrodynamic characteristics of the feed system and is set at nominally 50–70 msec. The closure commences with the energizing of the closing solenoid valve, which allows the unrestricted flow of nitrogen from the 600-psig source through the shuttle valve into the closing side of the cylinder and simultaneously opens the pneumatic valve, which rapidly vents the opening side. Control of the closing rate is obtained by restricting the pneumatic-vent-valve exhaust port with a fixed-size orifice.

The propellant valve was always installed close-coupled to the manifold inlet ports to keep the effective manifold volume to a minimum. A typical stand installation of the valve assembled with one of the injectors used in the RMIR program is shown in Fig. 11.

The instrumentation dynamic response required to obtain starting-transient information during this program was within the capability of standard bonded-strain-gage pressure transducers (properly coupled as described in Ref. 9 and 10) manufactured by the Taber Instrument Co.,[3] and turbine flow meters manufactured by the Waugh Engineering Co.[4]

Chamber and injector-manifold pressures were measured with transducer/coupling/oscillograph systems having an overall response capability of 65 cps flat to $\pm 2\%$. Additionally, at least one high-response (8 kc) p_c measurement was made during each firing. Transient flow measurements were obtained using 2½-in. flowmeters with maximum rated output frequencies of 400 cps. The output pulses were recorded on an oscillograph simultaneously with the above pressure information. These pulse data were manually reduced for flow information. Further details of these measurement systems are discussed in Ref. 2.

B. Analysis

If the hydraulic characteristics of the individual sides of the feed system described in Sect. IIA (Fig. 1) are analytically coupled to each other, it is possible to relate feed pressures, manifold volumes, and valve hydraulic characteristics in such a way that the criteria for a valve-opening transient that will prohibit flow overshoot and produce essentially simultaneous injection can be specified. These criteria can be derived as follows.

Consider that the total hydraulic transient is the sum of two periods, as illustrated in Fig. 12. The first comprises the time required to fill the manifold volume (includes line downstream of the valve), while the second is that period where total flow resistance includes the influence of the injector pressure drop and chamber pressure. It is assumed that the valve opening is very slow compared to the round-trip pressure-wave travel time between the valve and tank; hence fluid compressibility and line flexibility effects can be neglected. Also, the velocity head in the supply line is always considered to be small relative to the other pressure terms so that dynamic effects in the supply line can be ignored. Finally, for the initial period – i.e., manifold filling – it is also assumed that:

1. Individual tank pressures $p_{t_{ox}}$ and p_{t_f} remain constant.
2. No propellant is injected into the chamber until the manifolds are filled.
3. The pressure drop from the outflowing atmospheric gas is negligible. Hence individual manifold pressures $p_{i_{ox}}$ and p_{i_f} remain atmospheric during that period.

Then within these restrictions, the instantaneous volumetric flow rate for any element (i.e., line, valve or injector) of an individual flow circuit at any time during the total hydraulic transient can be expressed as

$$Q = C_d A \sqrt{\frac{2g_c\, 144 \Delta p}{\rho}} = \sqrt{\frac{\Delta p}{\rho/(C_d A)^2\, 2g_c\, 144}}$$

where

C_d = loss coefficient combining all loss effects within the element

A = discharge area of the element

Δp = static pressure difference across the element (including all energy conversions resulting in pressure losses)

For the purposes of this analysis a more convenient form of this flow equation is

$$Q = \sqrt{\frac{(\Delta p)_{h,v,i}}{\sigma\,(Z)_{h,v,i}}}$$

[3]North Tonawanda, New York.

[4]Van Nuys, California.

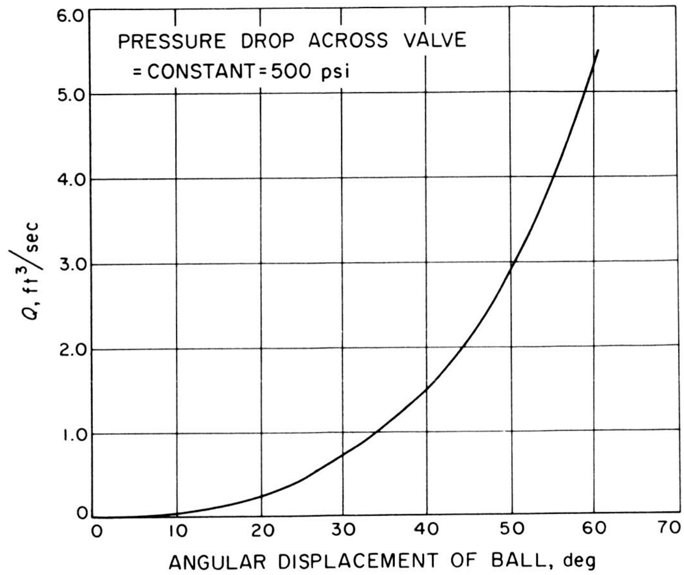

Fig. 10. Flow vs ball position, Hydromatics propellant valve

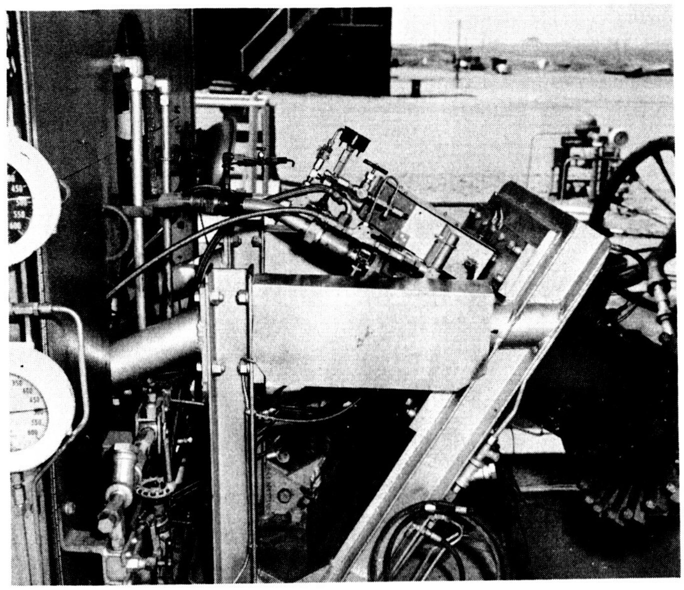

Fig. 11. Typical dual-ball-valve installation (RMIR Injector 4)

where $(Z)_{h,v,i}$ is a flow coefficient related to the loss coefficient and the flow area of the respective elements and is defined as

$$(Z)_{h,v,i} = \frac{62.435}{(C_d A)^2_{h,v,i}\, 2g_c\, 144}$$

Since the static pressure difference across the portion of the flow circuit of interest is equal to the summation of the pressure differences across the elements of the circuit, then for flow through a complete feed circuit (with p_c established),

$$\begin{aligned} p_t - p_c &= \Delta p_h + \Delta p_v + \Delta p_i \\ &= \sigma Z_h Q^2 + \sigma Z_v Q^2 + \sigma Z_i Q^2 \\ &= \sigma Q^2 (Z_h + Z_v + Z_i) \end{aligned}$$

and

$$Q = \sqrt{\frac{p_t - p_c}{\sigma (Z_h + Z_v + Z_i)}}$$

Thus a system flow coefficient may be defined as

$$Z = Z_h + Z_v + Z_i$$

For the manifold-filling segment of the transient, however, assumption (3) states that the pressure drop of the injector is negligible and assumption (2) implies that p_c remains zero. Therefore, at any time during that period

$$Z = Z_h + Z_v$$

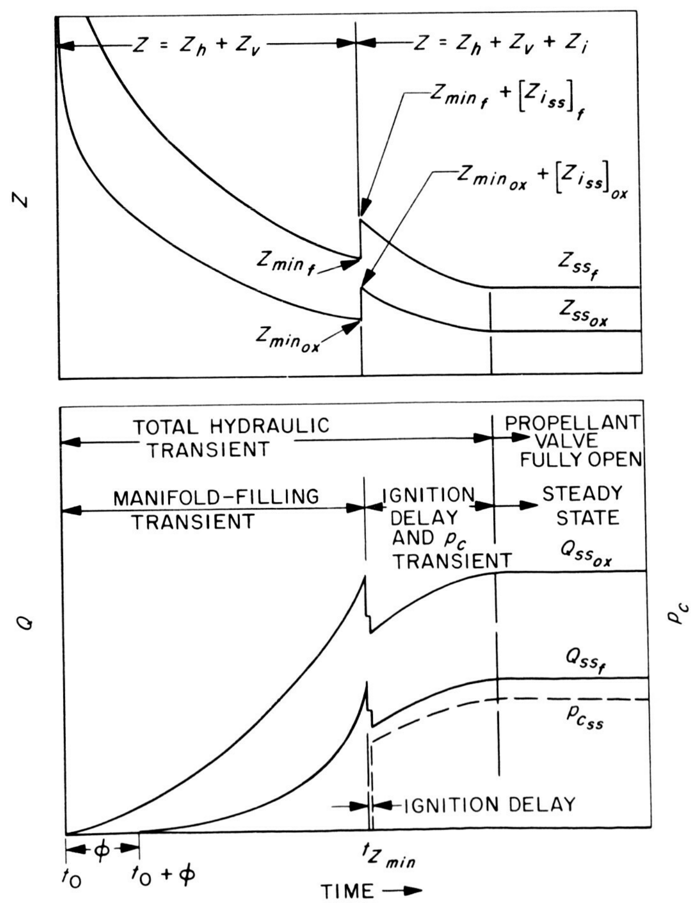

Fig. 12. The starting transient

and

$$Q = \sqrt{\frac{p_t}{\sigma Z}} = \sqrt{\frac{p_t}{\sigma (Z_h + Z_v)}} \tag{1}$$

Further, if it is assumed that the feed-line flow coefficient Z_h is a constant, but that the valve coefficient Z_v is a function of valve position $[(C_d A)_v]$ as the valve is opened, then Z may also be written as a function of time [i.e., $Z(t)$] for that period while the valve position is changing. Hence, Eq. (1) becomes

$$Q = \sqrt{\frac{p_t}{\sigma Z(t)}}$$

For prepressurized systems, the feed-supply pressure p_t is dictated by the steady-state run conditions, i.e., the sum of the overall system pressure drop and chamber pressure. During the manifold-filling period, the back pressure associated with the injector pressure drop and chamber pressure is absent. Thus the flow rates into the manifold during this period can become quite high unless the propellant valve is used as a flow-control device. Excessive filling flow rates lead directly to intolerably high initial-injection flows and if the filling flow is sufficiently high, waterhammer and fluid-acceleration pressures may be developed in the manifold, which may further modify the injected flow. These potential inertial phenomena result from the abrupt occurrence of the injector restriction at the completion of manifold filling and the consequent sudden reduction of the flow velocity in the manifold and supply lines. Since most of the injectors used in the RMIR program were high pressure-drop designs, they were quite susceptible to such effects so that need for adequate control of the hydraulic transient was accentuated.

A prediction of the tolerable flow rate for the initial portion of the transient is nearly impossible in view of the unpredictable effects influencing ignition delay, but it seems clear that a logical choice for the upper limit is the design steady-state flow rate. Thus, for purposes of this analysis this requirement can be satisfied by requiring that the value of Q must not exceed the desired run steady-state flow rate Q_{ss}, where

$$Q_{ss} = \sqrt{\frac{p_t - p_{c_{ss}}}{\sigma Z_{ss}}} \tag{2}$$

and

$$Z_{ss} = Z_{h_{ss}} + Z_{v_{ss}} + Z_{i_{ss}}$$

where the subscript *ss* indicates steady-state values (propellant valve fully open and injector flowing fully).

Then if Q is set equal to Q_{ss}, it follows from the combination of Eq. (1) and (2) that the minimum allowable value of Z during the filling period is

$$Z_{min} = \frac{Z_{ss}\, p_t}{p_t - p_{c_{ss}}} \tag{3}$$

which is dependent upon the transient properties of Z_v for control. Thus the propellant valve can serve as an appropriate control device during this first segment of the transient (prior to injection) as well as the latter one (through the ignition-delay and chamber-pressure transient) when it must in general satisfy a different set of requirements.

If t is the time at which the manifold volume V is just filled – i.e., the manifold-filling period – then

$$V = \int_{t_0}^{t} Q\,dt = \sqrt{\frac{p_t}{\sigma}} \int_{t_0}^{t} \frac{dt}{[Z(t)]^{1/2}} \tag{4}$$

and it is clear that the upper limit for the integral is in fact the minimum time that is permitted for the transient and is the time when $Z = Z_{min}$. Therefore, if a minimum time for the transient is a criterion to be satisfied, Eq. 4 becomes

$$V\sqrt{\frac{\sigma}{p_t}} = \int_{t_0}^{t_{Z_{min}}} \frac{dt}{[Z(t)]^{1/2}} \tag{5}$$

If it is further assumed that the time of initial injection for the two propellants is to be simultaneous and that the difference in the time interval between "manifold filled" and injection into the chamber for the two propellants is negligibly small (or alternatively, if the transit time for initial flow through the length of the orifices is essentially equal for both systems), then the control valves and system constants must be related by

$$\frac{V_{ox}}{V_f}\sqrt{\frac{p_{t_f}\,\sigma_{ox}}{p_{t_{ox}}\,\sigma_f}} = \frac{\displaystyle\int_{t_0}^{t_{Z_{min}}} \frac{dt}{[Z(t)_{ox}]^{1/2}}}{\displaystyle\int_{(t_0+\phi)}^{t_{Z_{min}}} \frac{dt}{[Z(t)_f]^{1/2}}} \tag{6}$$

where ϕ is the lead or lag of the fuel-control valve relative to the oxidizer valve.

Obviously, these relationships in themselves do not give $t_{Z_{min}}$ directly. However, if $Z(t)$ is known from experiment and analysis, or can be approximated, then it is possible to solve for $t_{Z_{min}}$ (assuming $Z(t)$ integrable) in terms of the system parameters. In general these parameters are determined from "other" considerations so that a reasonable value for $t_{Z_{min}}$ can be obtained. Conversely, if $t_{Z_{min}}$ is specified, then a compatible set of system parameters can be determined.

Note that in practice $[Z(t)]_{ox}$ cannot be identical to $[Z(t)]_f$ and ϕ cannot be zero as concurrent operating conditions except for the unique case where Z_{min}, V, and p_t/σ for both propellant systems are equal. Since there may be many conflicting factors which influence a final system design, it seems improbable that the latter equalities will often occur. Therefore, the arbitrary choice of identical valve-resistance transients and the simultaneous sequencing of the two control valves should not be made (as is often done) unless the other system parameters are sufficiently variable to permit satisfying Eq. (6).

During the second part of the hydraulic transient, mixture ratio becomes meaningful in a combustion sense as injection flow begins and the ignition and ultimately the chamber-pressure transients commence. During the early part of the manifold-filling interval, r may have ranged from 0 to ∞, since, depending on the differences in the respective manifold volumes and system hydraulic characteristics, only one of the two propellants may have flowed. If, however, (1) the manifold filling has proceeded in accordance with Eq. (6), and (2) fluid inertia effects are still assumed to be negligible, the instantaneous mixture ratio during the p_c transient will follow the relationship

$$r = \frac{\dot{m}_{ox}}{\dot{m}_f} = \frac{\sigma_{ox} Q_{ox}}{\sigma_f Q_f} = \left[\frac{Z_f \sigma_{ox}}{Z_{ox} \sigma_f}\left(\frac{p_{t_{ox}} - p_c}{p_{t_f} - p_c}\right)\right]^{1/2}$$

where Z_f and Z_{ox} are instantaneous values of the overall fuel-circuit and oxidizer-circuit flow coefficients, including the injectors, and p_c is the instantaneous value of chamber pressure.

An evaluation of r with respect to the intended steady-state value r_{ss} may now be obtained by examining the ratio r/r_{ss} at certain times in the p_c transient. This ratio is

$$\frac{r}{r_{ss}} = \left[\left(\frac{Z_{ss_{ox}}}{Z_{ss_f}}\right)\left(\frac{Z_f}{Z_{ox}}\right)\left(\frac{p_{t_f} - p_{c_{ss}}}{p_{t_{ox}} - p_{c_{ss}}}\right)\left(\frac{p_{t_{ox}} - p_c}{p_{t_f} - p_c}\right)\right]^{1/2} \qquad (7)$$

At the instant of manifold filling, when $Z_f = Z_{min_f}$, $Z_{ox} = Z_{min_{ox}}$ and $p_c = 0$, Eq. (7) yields a value of unity. However, in general, the ratio departs from unity as the injector resistance abruptly occurs [assuming a continuous and monotonic $Z_v(t)$] but approaches that value again as Z_f, Z_{ox}, and p_c approach their respective steady-state values. Therefore, the "worst" time in the p_c transient from the standpoint of mixture-ratio tracking is that time when each of those three variables is farthest from steady state. This time ($t = t^+_{Z_{min}}$) occurs at injection-flow onset when

$$p_c = 0$$

and

$$Z_f = Z_{min_f} + [Z_{i_{ss}}]_f \qquad (8a)$$

$$Z_{ox} = Z_{min_{ox}} + [Z_{i_{ss}}]_{ox} \qquad (8b)$$

The ratio r/r_{ss} at that time can be formulated in terms of the system parameters by combining Eq. (3), (7), and (8) and substituting 0 for p_c to give

$$\left[\frac{r}{r_{ss}}\right]_{t=t^+_{Z_{min}}} = \left[\frac{1 + \left(\dfrac{Z_{i_{ss}}}{Z_{min}}\right)_f}{1 + \left(\dfrac{Z_{i_{ss}}}{Z_{min}}\right)_{ox}}\right]^{1/2} \qquad (9a)$$

$$\left[\frac{r}{r_{ss}}\right]_{t=t^+_{Z_{min}}} = \left[\frac{1 + \left(\dfrac{p_{i_{ss}} - p_{c_{ss}}}{p_t}\right)_f}{1 + \left(\dfrac{p_{i_{ss}} - p_{c_{ss}}}{p_t}\right)_{ox}}\right]^{1/2} \qquad (9b)$$

It is apparent that unless the ratio of steady-state injector pressure drop to supply pressure is identical for the two propellant systems, the ratio r/r_{ss} will not be unity at the inception of the p_c transient. However, it is also apparent that because this pressure ratio can never exceed unity, and because of the ½ power of the right side of Eq. (9), deviations from equality of the two pressure ratios by as much as a factor of 2 will produce maximum r/r_{ss} deviations from unity of only 15%. Further, it is noted that this maximum deviation occurs when $p_c = 0$. If the initial chamber-pressure rise is nearly a step discontinuity and is nearly simultaneous with the onset of injected flow (i.e., negligible ignition delay), the deviation of r/r_{ss} from unity is rapidly reduced because the chamber pressure rapidly approaches $p_{c_{ss}}$. The maximization of the initial flow rates (hence combustion rates) to provide this steep p_c transient (albeit without overshoot) is of course an objective of the filling-flow criterion of Eq. (6); hence, mixture ratio can be essentially constant during the p_c transient if that criterion is satisfied.

III. CRITERIA LIMITATIONS

In the preceding discussion, several assumptions were made so as to simplify the analysis. The assumptions are believed to be justified; however, there are at least four conditions that may tend to modify the application of the derived relations. These are:

1. High-vapor-pressure propellants or space (vacuum) conditions.
2. Marginal propellant hypergolicity (or ignition).
3. Discontinuous initial injection.
4. Hydrodynamics effects.

A. High-Vapor-Pressure Propellants

No accounting has been made for high-vapor-pressure propellants (cryogenics) or high-vacuum conditions (space environment), both of which tend to promote propellant vaporization in the injector manifold and during the ignition-delay period. It is recognized that the effects of transient vaporization on ignition delay are unpredictable in any event, but the degree of the effects may be increased many times under conditions promoting high vaporization rates. Though no attempt will be made to elucidate these vaporization processes, it is pointed out that these effects may modify the application of the criteria as discussed herein.

B. Marginal Hypergolicity

The accepted meaning of the term "hypergolic propellant combination" as spontaneously reactive indicates that propellants so classified exhibit an insignificant combustion lag at ambient conditions (to differentiate between overall ignition delay and basic reaction rate). This, of course, is not the case and there are finite lags which can be significant whenever short starting transients are required.

Propellants having long combustion lags (i.e., marginally hypergolic) may not be able to tolerate as steep a starting-flow transient as provided by the flow criteria. In this case a slower valve-opening rate would be indicated to reduce the propellant accumulation to a tolerable quantity.

"Nonhypergolic propellants" require a separate ignition source. The variations in ignition systems preclude a discussion of them here, but most of these systems would appear to be easily integrated with the transient-flow criteria.

C. Discontinuous Injection

The validity of the assumption that no flow occurs from the injector until the manifolds (including the orifice volume) are full is probably dependent on the details of the injector design. There may also be a dependency on the physical properties of the propellants and the temperature and pressure conditions in the combustion chamber during the initial propellant injection. Discontinuous initial injection may occur as the manifolds fill and the propellant is entrained in the expulsion of the gas-filled ullage through the orifices. Even if the manifolds are vacuum filled (space condition), some "dribbling" is apt to occur due to the propellant entry momentum into the manifolds.

The results of this kind of injection would generally be small perturbations to the smooth rise of the p_c transient rather than hazardous p_c overshoot. It is conceivable, however, that a gross separation of the orifices initially flowing would prohibit adequate mixing and thereby increase the propellant accumulation. Some modification of the application of the criteria might then be necessary to allow for this effect.

D. Hydrodynamic Effects

The assumption of the applicability of the steady-state flow equation to the hydraulic-transient period restricts the analysis presented here to systems wherein hydrodynamic effects caused by fluid inertia and system elasticity are negligible.

In situations where this assumption is not valid, it is necessary to consider the waterhammer which appears both upstream and downstream of a fast-acting control valve. The upstream wave is initially a rarefaction travelling to an appropriate "end" (in Fig. 1, the tank outlet) from which it will ultimately be reflected as a high-pressure wave. Thus, if coincidently the valve-opening time were $2L/a$ so that the head rise at the valve due to this wave was the maximum possible of $0.23\ p_t$ (Ref. 11), then the instantaneous flow rate across the valve could be increased by some 10%. Consequently the injected flow rate could be influenced if this effect were not otherwise masked by the downstream effects.

Problems arise in the portion of the manifold downstream of the valve only when the flow velocities are appreciable at the instant the manifold is filled. For systems where the manifold-filling time is of the same magnitude as the valve-opening time and the injector flow area appears as a sudden restriction to the flow, the waterhammer pressures produced at that time could be appreciable. However, it should be noted that if the control valve is used to limit the flow to the steady-state value, then in general the velocity downstream of the valve is low, and the head loss at the valve at that instant is quite high (steady-state injector drop plus chamber pressure) so that the net effect on injected flow should be small. This was certainly the case for the experiments reported here.

IV. NONREACTIVE FLOW-TRANSIENT TESTS

The starting-flow-transient criteria discussed in the preceding two Sections provide a useful tool for system design. After the design is established, however, and prior to the commitment of an engine to the initial firing, a verification that the design meets the criteria is highly desirable. To this end a simple testing technique was developed during the Rocket Motor Injection Research program.

The technique is based on the assumption that the actual firing volumetric flow transient during the manifold-filling period can be approximated by the substitution of nonreactive fluids (e.g., water) for the propellants. For this purpose it is assumed that equivalent transient times are achieved if the acceleration effects are similar. Thus the volumetric flow-transient approximation is provided by modifying the design feed-system supply pressure to the value

$$(p_t)_T = (p_t)_D \times \frac{\sigma_T}{\sigma_P} \tag{10}$$

where the subscripts T, D, and P refer respectively to test, design, and propellant. This does not provide equivalent steady-state volumetric flow rates due to the absence of chamber pressure during the nonreactive tests, but since the portion of the transient of interest extends only through the time of initial injection, the change in flow is of no consequence as long as the manifold-filling times are actually duplicated.

In order for the system design to meet the flow-transient criteria, the peak test volumetric flow rates achieved during the manifold-filling period should not exceed the design steady-state propellant volumetric flows and there should be no injection lead of either propellant. Some means of measuring these characteristics is therefore required.

Both characteristics of the transient can be determined by single measurements on each side of the feed system – a transient injector-manifold-pressure measurement. Figure 13a shows an idealized representation of both a nonreactive and an actual rocket-engine starting transient (no ignition delay) which meets the flow-transient criteria. The figure includes the flow-rate and injector-pressure transients for one side of the propellant system as well as the chamber-pressure transient. For comparison, transients which do not satisfy the flow criteria are shown in Fig. 13b.

Since it was assumed that the filling transient for the nonreactive test duplicates the firing transient, the flows are shown to be identical during this time. At the instant just prior to filling completion, the instantaneous flow rate $(Q_0)_T$ is

$$(Q_0)_T = (Q_{ss})_D = \sqrt{\frac{(p_t)_T}{\sigma_T Z_{min}}} \tag{11}$$

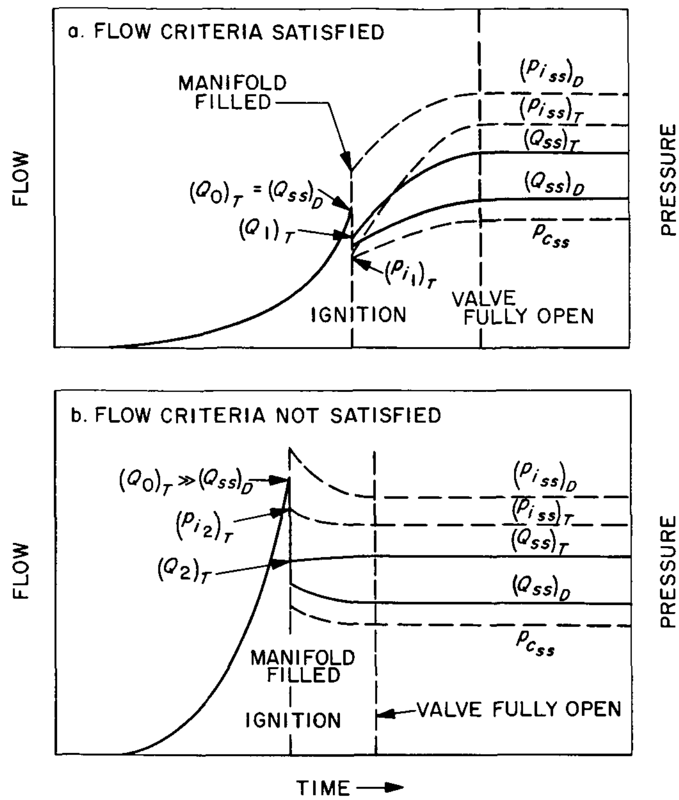

Fig. 13. Starting-flow transients for nonreactive tests

while at the instant following filling completion, the flow rate $(Q_1)_T$ is (since waterhammer effects can be neglected)

$$(Q_1)_T = \sqrt{\frac{(p_t)_T}{\sigma_T\,(Z_{min} + Z_{i_{ss}})}} = \sqrt{\frac{(p_{i_1})_T}{\sigma_T\,Z_{i_{ss}}}} \tag{12}$$

A comparison of the two values of Q shows the step reduction in flow indicated in Fig. 13a. After this time the test flow transient diverges from the firing transient due to the absence of chamber pressure in the nonreactive test and follows the continued opening of the valve, eventually reaching a steady-state value $(Q_{ss})_T$ which is

$$(Q_{ss})_T = \sqrt{\frac{(p_t)_T}{\sigma_T\,Z_{ss}}} = \sqrt{\frac{(p_{i_{ss}})_T}{\sigma_T\,Z_{i_{ss}}}} \tag{13}$$

Thus the ratio $(p_{i_1})_T/(p_{i_{ss}})_T$ for a flow transient satisfying the criteria is, from Eq. (12) and (13),

$$\frac{(p_{i_1})_T}{(p_{i_{ss}})_T} = \frac{Z_{ss}}{Z_{min} + Z_{i_{ss}}}$$

The appearance of the injector-pressure transient for a flow transient that does not satisfy the flow criteria is shown in Fig. 13b. Here the flow-coefficient transient (valve-opening transient) has allowed the flow to exceed $(Q_{ss})_D$ prior to the manifold filling completion; i.e., $Z_2 < Z_{min}$. Hence,

$$\frac{(p_{i_2})_T}{(p_{i_{ss}})_T} > \frac{Z_{ss}}{Z_{min} + Z_{i_{ss}}} \tag{14}$$

In view of the assumption that no orifice flow occurs until the manifold fills, it is consistent to expect that the orifice flow will commence nearly simultaneously with the manifold-pressure rise. Comparisons of high-speed movies of the orifice outlets near the completion of manifold filling with the injector-pressure transients have shown this to be essentially correct. Thus a measurement of injection lead can also be determined from the recorded injector-pressure transients.

In lieu of, or in conjunction with, the injector-pressure-transient measurement a turbine flowmeter system can be used to determine the flow, providing the output frequency and dynamic response are sufficiently high to resolve the transient. These systems provide flow information that is basically the volumetric flow rate integrated over some convenient time period, the minimum period being the interval between individual output pulses.

The technique presented here has proved to be invaluable for purposes of verifying the estimated valve-transient characteristics and for establishing these pertinent system parameters in new complicated manifold configurations.

In summary it may be stated that once the flow-control criteria and the water-flow testing technique were established and incorporated into the RMIR program, starting transients were consistent and predictable over the range of test conditions used. Safe starting transients were achieved for each initial hot firing with small adjustments optimizing the transients for subsequent runs.

V. APPLICATION TO REAL SYSTEMS

The Rocket Motor Injection Research program was concerned with the performance evaluation of nine different injectors in various combinations with a number of different propellant combinations. The various propellants are listed in Table 2. With one exception the propellant combinations used were hypergolic and required no ignition system. The nonhypergolic combination, $B_5H_9 + N_2H_4$, utilized an N_2O_4 starting system consisting of a set of three spray nozzles, which directed the N_2O_4 across the chamber near the impingement-point plane at a flow rate of approximately 10% of the nominal run total flow rate. The N_2O_4 flow was terminated after ignition occurred.

Transient wall-temperature measurements appropriate to the determination of local heat transfer were of prime interest so that short, reproducible combustion transients were essential. Note that the temperature transient required for this purpose is really the temperature-time history subsequent to a step change from one steady-state configuration of heat conduction through a wall (i.e., ambient conditions) to a second configuration which is assumed to be steady-state combustion. Also, to obtain performance evaluations over wide mixture-ratio ranges, the initial conditions, and hence relative transients, varied substantially from run to run.

For each new injector configuration a series of water-pumping tests was conducted to verify the suitability of the transient. For this purpose the test-tank pressures were maintained constant according to Eq. (10) for a series of tests, while overall valve-opening rate and sequencing were varied as independent parameters until the particular combination was found that provided flow transients approximating but not exceeding the design run-condition flow rates and that also provided simultaneous initial injection flow.

Table 2. RMIR program propellant combinations

Hypergolic	Nonhypergolic
SFNA (81.3–84.5% HNO_3; 14.0% NO_2; 2.5% H_2O; 0.6% HF) + Corporal Fuel (46.5% Aniline; 46.5% furfuryl alcohol + 7% hydrazine) SFNA + diethylenetriamine (DETA) SFNA + unsymmetrical dimethylhydrazine (UDMH) SFNA + JPX (40% UDMH; 60% JP-4)[a] Nitrogen tetroxide (N_2O_4) + Hydrazine (N_2H_4) N_2O_4 + UDMH N_2O_4 + JPX[a]	Pentaborane (B_5H_9) + Hydrazine (N_2H_4) (N_2O_4 ignition system)

[a]Marginally hypergolic

As a specific example of the application of the transient criteria and testing technique to the RMIR program, the flow system and results will be discussed for only one of the typical injectors of the program — i.e., Injector 5 — but these results are typical of all the system configurations that were evaluated.

A. Nonfiring Flows

Table 3 shows the computation of Z_{ss}, Z_{min}, and the predicted ratio of initial to final injection pressure for the optimum transient for both sides of the system. These computations are based on the injector design specifications listed in Table 1 and the known feed-line characteristics Z_{h_f} and $Z_{h_{ox}}$.

Figure 14 shows a portion of the oscillograph record of the Injector 5 flow-transient test most nearly meeting the

Table 3. Injector 5 and system hydraulic characteristics

Fuel side (Corporal Fuel, $\sigma_P = 1.072$):

$Z_{h_{ss}} = 141$ $\qquad (p_t)_D = 740$ psig

$Z_{i_{ss}} = 2700$ $\qquad p_{c_{ss}} = 300$ psig

$$Z_{ss} = Z_{h_{ss}} + Z_{i_{ss}} = 2841$$

$$Z_{min} = \frac{Z_{ss}(p_t)_D}{(p_t)_D - p_{c_{ss}}} = \frac{2841\,(740)}{440} = 4780$$

$$\frac{(p_{i_1})_T}{(p_{i_{ss}})_T} = \frac{Z_{ss}}{Z_{min} + Z_{i_{ss}}} = \frac{2841}{4780 + 2700} = 0.38$$

Oxidizer side (SFNA, $\sigma_P = 1.553$):

$Z_{h_{ss}} = 109$ $\qquad (p_t)_D = 642$ psig

$Z_{i_{ss}} = 305$ $\qquad p_{c_{ss}} = 300$ psig

$$Z_{ss} = Z_{h_{ss}} + Z_{i_{ss}} = 414$$

$$Z_{min} = \frac{Z_{ss}(p_t)_D}{(p_t)_D - p_{c_{ss}}} = \frac{414\,(642)}{342} = 778$$

$$\frac{(p_{i_1})_T}{(p_{i_{ss}})_T} = \frac{Z_{ss}}{Z_{min} + Z_{i_{ss}}} = \frac{414}{778 + 305} = 0.38$$

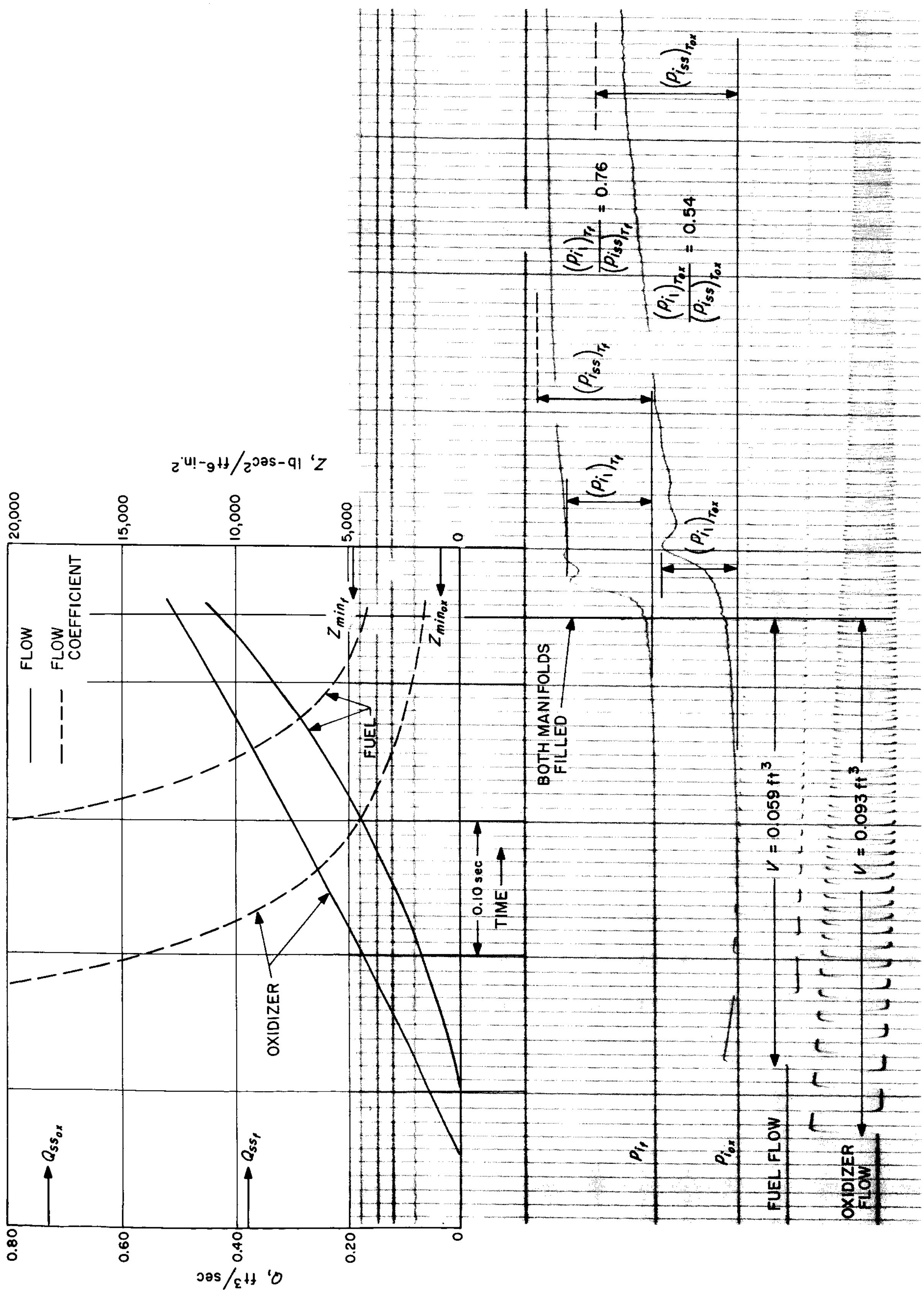

Fig. 14. Water-flow transient test, RMIR Injector 5, test 11, pre-B531

transient criteria. Also shown in Fig. 14 are the reduced-flow and flow-coefficient transients during the manifold-filling period plotted on the record time base. Completion of manifold filling occurred simultaneously for both sides, as indicated by the respective accumulated flowmeter pulse counts; however, a small fuel-injection lead of 10–15 msec is inferred from the injector-pressure transients. This amount of lead approaches the accuracy of the determination of lead from the pressure measurement and is considered insignificant—especially in view of the simultaneity of manifold filling as shown by the flow measurements.

The fuel-flow transient is slightly steeper than the requirement of the criteria since the flow exceeds Q_{ss_f} by about 13% at filling completion. This steepness is also reflected in the flow-coefficient transient, when Z_f at this same time is slightly smaller than the computed Z_{min_f}. Conversely, the oxidizer transient is somewhat less steep than desired, as indicated by both Q and Z.

The difference in the two flow transients is the result of the inability of the propellant-valve drive-linkage to provide for individual ball-opening-rate control independent of the lead adjustment. For this injector the consequence is an accommodation to the combined transient criterion [Eq. (6)] on the part of the oxidizer system whereby the overall valve-opening transient is adjusted for the system with the larger Z_{min}, while the valve-opening lead is provided for the system with the larger V.

The measured injector-pressure ratios (i.e., the ratio of manifold pressure at ignition to the steady-state value) of 0.76 and 0.54 respectively for the fuel and oxidizer sides are high compared to the predicted ratio of 0.38 for both sides (Table 3). Note, however, that the pressures actually commence to rise prior to the completion of manifold filling due to the expulsion of ullage air from the manifold through the orifices together with the commencement of orifice filling. If $(p_{i_1})_T$ is taken as the pressure rise from the time of filling completion, the measured ratios are 0.68 and 0.45 respectively.

Although the fuel-side ratio can be expected to be somewhat high due to the slightly too-steep flow transient, the injector-pressure ratios for both sides are greater than the prediction as a result of another opening characteristic of the dual-ball propellant valve. A small step increase in the valve opening is always observed just as the manifolds fill because of a change in the required ball-opening torque as the pressure load on the ball and its seal decreases while the injector resistance increases. The effect of the step decrease in valve resistance is, of course, reflected in the increase in flows and hence the injector pressures.

B. Engine Start Transient

The result of applying the flow transient shown in Fig. 14 to an actual engine firing is illustrated in Fig. 15, which shows the oscillograph record of the starting transient for run B535 of the RMIR program using Injector 5 at near-design conditions.

Note that the start is achieved without the chamber pressure exceeding the steady-state value, while 95% of the final p_c is obtained in less than 350 msec. The several cycles of oscillation following the initial p_c rise is attributed to the feed-system dynamic characteristics. The rapid damping of the oscillations is enhanced by the high pressure drop of the injector.

Essentially simultaneous initial injection is indicated by the occurrence of ignition near the time that both injector pressures start to rise. This injection simultaneity is also indicated by the close agreement of accumulated flows to the respective manifold volumes at the time of ignition.

These data serve to illustrate the application of the starting-transient criteria to only one injector and propellant combination, but are typical of the results achieved in a number of different configurations. Minor exceptions were encountered in the case of N_2O_4 + JPX propellant combination and on those occasions where limitations in the operational characteristics of the propellant valve necessitated compromising the desired valve transient. In the case of the JPX systems, it was shown that the problem was related to the marginal hypergolicity of that fuel, which allowed excessive combustion lags and hence propellant accumulations that resulted in relatively hard starts.

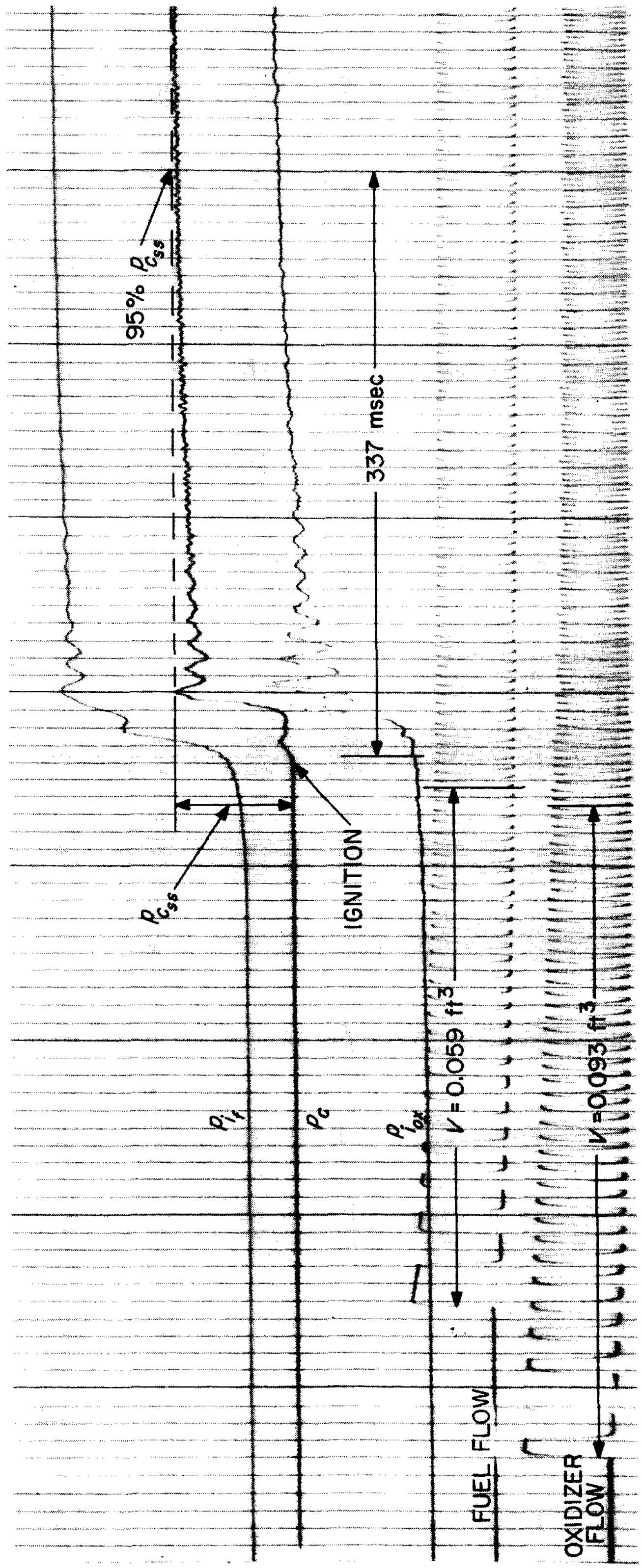

Fig. 15. Oscillograph record of Injector 5 firing starting transient, run B-535

VI. CONCLUSIONS

1. Chamber-pressure overshoot during the starting transient is primarily the result of high propellant-flow rates and/or injection lead during the ignition-delay period, allowing excessive accumulation of unreacted propellants in the combustion chamber during that same period.

2. Propellant accumulation can be minimized if the starting-flow transient is controlled to provide:

   (a) A monotonically increasing individual *injected* propellant flow rate for which the peak amplitude approximates, but does not exceed, the steady-state flow rate desired for the run.

   (b) A constant mixture ratio of *injected* propellant that is equal to the intended value.

   (c) Simultaneous initial injection of the propellants into the chamber; i.e., no propellant-injection lead.

   If it is also assumed that ignition is simultaneous with injection into the chamber, then in a practical sense propellant accumulation can be eliminated when these several conditions are satisfied.

3. The selection of a suitable opening rate together with a sequenced opening of the individual sides of a dual propellant valve will provide the flow control necessary to prevent such accumulations.

4. The transient pressure-drop characteristics of the control valve can be related to system constants by requiring that

$$Z_{min} = \frac{Z_{ss}\, p_t}{p_t - p_{c_{ss}}}$$

and

$$\frac{V_{ox}}{V_f}\sqrt{\frac{p_{t_f}\,\sigma_{ox}}{p_{t_{ox}}\,\sigma_f}} = \frac{\displaystyle\int_{t_0}^{t_{Z_{min}}} \frac{dt}{[Z(t)_{ox}]^{1/2}}}{\displaystyle\int_{(t_0+\phi)}^{t_{Z_{min}}} \frac{dt}{[Z(t)_f]^{1/2}}}$$

5. Nonreactive flow-transient tests provide a relatively simple technique for predicting reactive starting transients without the risk of expensive hardware damage.

NOMENCLATURE

a pressure-wave propagation velocity, ft/sec

A area, in.^{2}

C_d loss coefficient

d diameter, in.

g_c constant of proportionality in Newton's second law of motion,

$$32.174\,\frac{\text{lbm-ft}}{\text{lbf-sec}^2}$$

L length, in. or ft

$\dot{m}$ mass rate of flow, lbm/sec

NOMENCLATURE (Cont'd)

p pressure, psig

Q volumetric rate of flow, ft^3/sec

r mixture ratio, defined as $\frac{\dot{m}_{ox}}{\dot{m}_f}$

t time, sec

V manifold volume, ft^3

Z flow coefficient, defined as $\frac{62.435}{(C_d A)^2 \, 2g_c \, 144}, \frac{\text{lbf-sec}^2}{\text{ft}^6\text{-in}^2}$

σ specific gravity based on a value of ρ for water at 4°C of 62.435 lbm/ft^3

ρ mass density, lbm/ft^3

ϕ timewise lead or lag of fuel-control valve relative to the oxidizer valve, sec

Subscripts

0 initial condition or zero

1 time of manifold-filling completion, optimum-flow transient

2 time of manifold-filling completion, nonoptimum-flow transient

c chamber (except when subscript for g_c)

f fuel

i injector

h line

min minimum

ox oxidizer

ss steady state

t tank

v valve

T nonreactive test condition

D design condition

P propellant

Superscripts

$+$ small increase

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